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A review of available methods and development on energy storage; technology update

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ABSTRACT

Energy storage becomes a key element in achieving goals in energy sustainability that lead to energy and cost savings. This paper discusses various types of energy storage including compressed air energy storage (CAES), flywheel energy storage (FES), pumped hydro energy storage (PHES), battery energy storage (BES), flow battery energy storage (FBES), superconducting magnetic energy storage (SMES), super capacitor energy storage (SCES), hydrogen energy storage, synthetic fuels, and thermal energy storage (TES) with additional information about the recent update of the technology. In the final part of this paper, the comparison and barriers to deploying the technologies are also given in order to give a better view about the energy storage technique.

Contents

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1. Introduction

Energy and environment have been forecasted to become two of the most challenging and major issues of the world in the future [1–4]. According to British Petroleum, fuel consumption was growing significantly in the last 30 years from 6630 Mtoe in 1980 to almost double which reach 11,630 Mtoe in 2009 [5]. On the other hand, the total CO_2 gas emissions increased massively from 9.396 million metric tons in 1960 to 32.083 million metric tons in 2008 [6]. For the past few decades, efforts have been made in order to innovate and create new technologies to alleviate environmental problems, energy shortages and reducing the high cost of new power plants. Many research and scientific works have been done to identify and implement the most suitable technology to rectify some of the problems [7–12]. Furthermore, the need for storing the energy waste from a variety of industrial, commercial or domestic processes and minimizing the loss of energy has a very significant impact to the world. In this respect, energy storage technology has attracted attention from researchers due to its capability in reducing energy consumption, costs and may be used as a substitute of another energy source [13].

2. Energy storage

2.1. Current status of energy storage

The drive of becoming the world leader in the clean energy industry has seen some competitive efforts between the researchers to increase energy efficiency, reduce greenhouse gas emission and promoting a cleaner and more sustainable energy generation. Certain types of energy storage such as pumped-storage hydroelectricity are one of the oldest ESS technologies that have been employed in the electricity grid.

To gain a better view of the world's energy storage scenario, a comparative estimation of current installed capacity of worldwide energy storage plant is shown in Fig. 1 [14].

Electricity transmission and contribution sector (power quality and energy management) and transport sector are the potential areas where energy storage system (ESS) can be fully utilized [15]. ESS enhances the existing power plant and at the same time prevents expensive upgrades [16]. ESS could act as a regulator that manages the fluctuations of electricity from renewable energy resources which has prevented their market penetration. With the introduction of ESS, renewable energy sources can be used to aid the transition for a newer and cleaner energy generation technology. However, a number of reasons such as high capital cost and lack of experience hinder the commercialization of ESS. Yet, the use of ESS is expected to rise in the near future due to renewable energy and power quality is becoming increasingly important [15].

Various characteristics of different technologies pertaining to energy storage devices have enabled them to be used for different types of applications depending on the application's specific parameters. Parameters such as energy and power density, response time, cost and economies scale, lifetime, monitoring and control equipment, efficiency and operating constraint are the factors of choosing the most suitable type of technology [17].

2.2. Energy storage and GHGs reduction

As described in the previous section, ESS technologies can be used for Power Quality or Energy Management purposes. Electrical energy storage technologies become a key device to increase the efficiency of electrical utilization due to the capability to produce electricity reserve. According to the report from the International Energy Agency, it is predicted that the world's electricity consumption increase significantly from 14,781 billion kWh in 2003 to 21,699 in 2015 and 30,116 billion kWh in 2030 to 65% of energy supplies coming from fossil fuel. As a result, GHG emission from energy industry will increase about 55% between 2004 and 2030 with oil and coal as the main contributor of global CO_2 emission

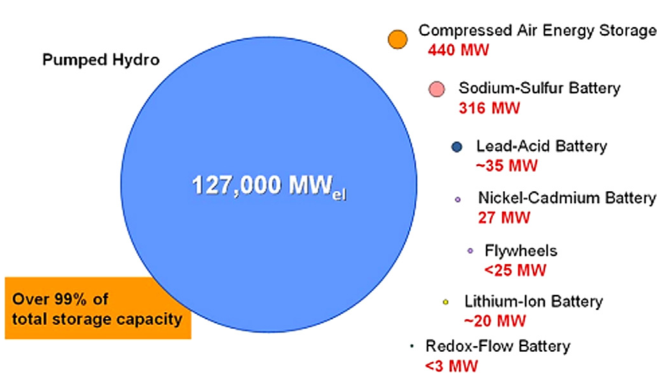


Fig. 1. Worldwide installed storage capacity for electrical energy [14].

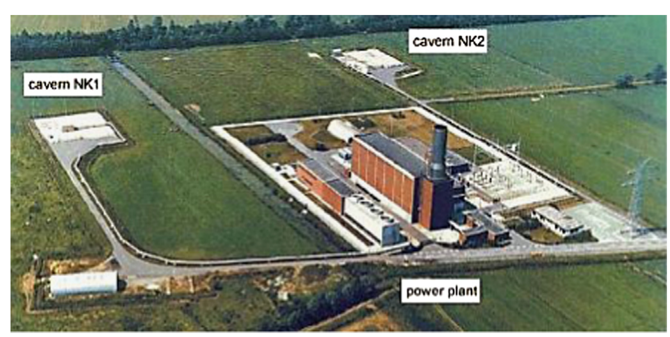


Fig. 2. CAES plant in Huntorf, Germany.

Fig. 3. CAES plant in McIntosh, Alabama.

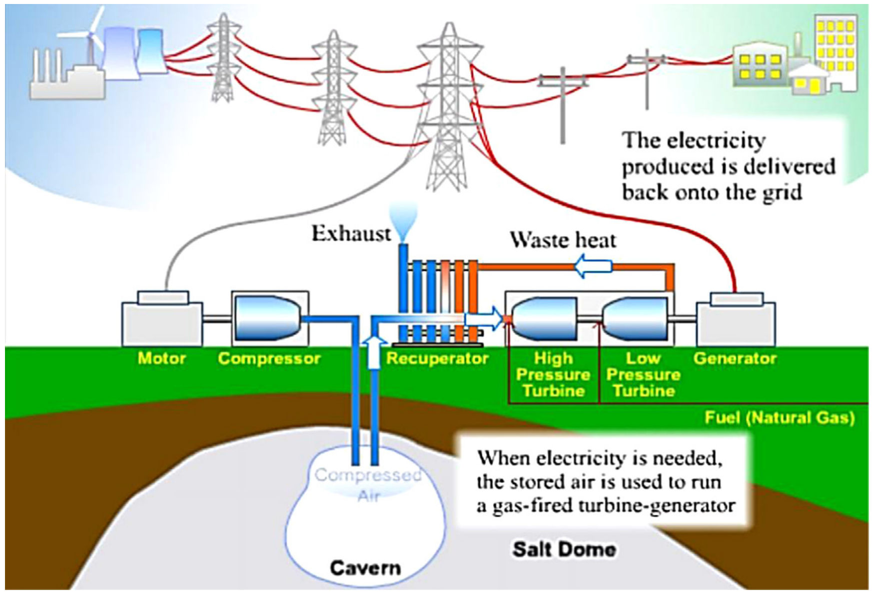


Fig. 4. CAES plant schematic diagram [27].

Table 1
CAES plant costs for various storage media and plant configurations.

Reservoir	Size (MW)	CPRC ($/kW)	CESC ($/kW)	ST (h)	CC ($/kWe)
Salt	200	350	1	10	360
Porous media	200	350	0.1	10	351
Hard rock	200	350	30	10	650
Surface piping	50	350	30	3	440

[18]. It is clearly shown that by optimization of energy supply, stabilization of transmission and grid distribution, and GHG emission reduction can possibly be achieved by this technology [16,19].

ESS also seems to be a favorable alternative to reduce fuel consumption for the gasoline fueled vehicle. The transportation sector was blamed for 23% of world CO_2 emission from fuel combustion in 2005 dominated by the road sector [20]. Although energy storage demands in the transport sector are relatively small compared to the electricity sector, the applications into the Transport and Mobility sector expected to increase system efficiency and reduce greenhouse gas emission significantly. A number of technologies are being considered for transport purposes, including batteries, super capacitors, hydrogen and flywheels [16].

3. Mechanical energy storage

3.1. Compressed air energy storage (CAES)

Compressed air energy storage (CAES) was introduced in 1970s to provide load following and to meet peak demand [21]. The first plant of CAES was installed in Huntorf, Germany with a capacity of 290 MW to support a nuclear plant and capable to support electricity grid for 3 h. The second plant of CAES was built in 1991, in McIntosh, Alabama with a 110 MW capacity for 26 h [22,23]. The CAES plants in Huntorf and Alabama are shown in Figs. 2 and 3. Although both of the plants uses solution-mined salt caverns for the purpose of air storage, the Alabama plants uses recuperator (exhaust gas heat exchanger) to reduce the fuel consumption up to 25% that used to reheat the air after it comes out of the air storage cavern [24,25].

The CAES basic operation is almost similar to a conventional gas turbine. While natural gas is essential to compress in conventional gas turbine, CAES pre-compresses the air using off-peak electrical power from the gridline and stores it in large storage reservoirs. As a result, cheaper off-peak base load electricity is used rather than expensive gas to compress the air. The reservoir can be hard rock cavern, salt cavern, depleted gas fields or an aquifer. Hard rock cavern offers a higher price than the others which accounted 60% more than salt cavern. On the other hand, aquifer cannot store high pressure air that is resulting in lower energy capacity. Furthermore, the advantages of salt cavern that can be designed to follow the specific requirement by using fresh water to dissolve the salt make this type preferable, although the process is long and expensive [15]. The schematic diagram of CAES basic operation is shown in Fig. 4 [26].

Table 1 shows the capital cost of a CAES plant for a various storage media and plant configurations [28].

Although the technology is not free from producing carbon footprint due to a small amount of gas needed to heat the incoming air before entering the turbine, this technology is able to produce electricity three times larger than a conventional gas turbine for a given amount of fuel [15]. In addition, fast reaction time usually less than 10 min and capable to undertake frequent start-up and shut down make this technology ideal for large bulk energy supply and demand [19]. The overall system of a CAES that coupled with other energy sources however may increase the total cost of investment due to the complexity of the large plant [29]. The introduction of a concept called the advance adiabatic (AA) into the CAES design system enables the turbine to run without the added gas. The AA-CAES system utilizes Thermal Energy Storage (TES) device to absorb the heat from the hot compressed air and reused the energy to reheat the air before expansion. This is the major difference between the AA-CAES and CAES conventional system which uses inter and after cooling to remove the heat and discard the excess energy that could be saved in the environment [30,31]. The first project of AA-CAES plant called “ADELE’ was constructed by RWE Power, General Electric, Züblin and DLR in Stassfurt, Anhalt with storage capacity of 360 MWh and an electric output of 90 MW [32]. The breakdown of the technological development of CAES can be seen in Table 2 [33].

According to various studies, the limited market penetration of this technology is due to the lack of awareness of the utility

Table 2
CAES development around the world.

System	Description
CAES – conventional	The 1st generation CAES concept successfully operated in Huntorf and Alabama.
CAES – Advanced 2nd generation with “extracted from expander” air injection	The design is based on the 1st generation with multiple air expanders for driving electric generators, with the air extraction for the combustion turbine power augmentation.
CAES – Advanced 2nd generation with inlet chilling	This design using multiple air expanders with exhausted cold air being directed into the combustion turbine compressor inlet flows providing power augmentation due to inlet chilling.
CAES – Air injection with expander extraction	The difference with bottoming cycle concept that air injected into the CT is extracted from HP expander exhaust.
CAES – Adiabatic	Adiabatic CAES using no fuel to convert stored compressed air. Cooling the compressor and heating the stored air is achieved by thermal storage.
Small CAES – Pipe storage	CAES plant utilizing air injection into the solar mercury gas turbine and the storage of compressed air in pressured vessels instead of the cavern.

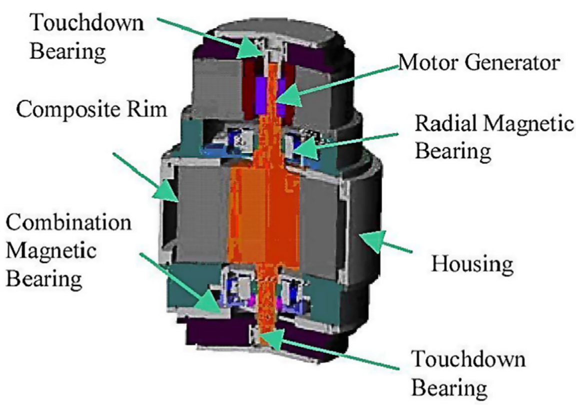


Fig. 5. Flywheel device components [28].

Table 3
Candidate materials for flywheel [65].

Material	Density (kg/m^3)	Tensile strength (MPa)	Max energy density (for 1 kg) (MJ/kg)	Cost ($/kg)
Monolithic material				
4340 steel	7700	1520	0.19	1
Composites				
E-glass	2000	100	0.05	11.0
S2-glass	1920	1470	0.76	24.6
Carbon T1000	1520	1950	1.28	101.8
Carbon AS4C	1510	1650	1.1	31.3

Table 4
Different types of magnetic materials [65].

Material	Density (kg/m^3)	Tensile strength (MPa)	Remanence (T)
Sintered neodymium–iron–boron	7400–7600	80	1.08–1.36
Sintered samarium cobalt	8000–8500	60	0.75–1.20
Sintered ferrite	4800–5000	9	0.20–0.43
Injection molded composite (Ni–Fe–B)	4200–5630	35–59	0.40–0.67
Compression molded composite (Nd–Fe–B)	6000	40	0.63–0.69
Injection molded composite ferrite	2420–3840	39–78	0.07–0.30

planner. In addition, the underground geology is likely perceived a lot of risk in the development of this technology [21,34]. This occurs on the Iowa Stored Energy Park (ISEP) project which was terminated on July 28, 2011 due project site geology limitations after eight years of development [35,36]. Moreover, very few engineers are aware of the fact that CAES sites are actually relatively common [34]. Due to these reasons, the highest potential market value of CAES technology is not explored to the fullest. Additionally, there are numerous studies that have been carried out by many researchers to develop CAES technology into a readily available technology with better efficiency and reduced investment costs and can be found in Ref. [37–54].

Other than power utilization sector, CAES technology also has been developed for other sector such as a vehicle. The Zero-Pollution MDI Air Car, invented in France and licensed by Tata Motors in India used compressed air instead of explosion to move the pistons. Unfortunately, the development is hindered by some difficulties in terms of vehicle range and cooling [55].

3.2. Flywheel energy storage (FES)

Flywheel energy storage technology has been experimented since the 1950s where several experimental buses called “gyrobuses” have been built using the flywheel design principle [56]. The capacity of a flywheel as a storage system may be used as a standalone energy storage, coupled with distributed generation assets or in a hybrid configuration with other storage medium i.e. batteries. The energy stored by accelerating the rotor and maintaining the energy in the system at very high speed as inertial energy [57]. Based on the speed, FES can be divided into high speed FES and low speed FES. High speed FES provides a long period time of storage but low power capacities and contrary for low speed FES [58,59]. Flywheel material, geometry and length are the key factors of FES which straightly affect the quantity of flywheel specific energy and energy storage [60]. The schematic of FES device is shown in Fig. 5.

Flywheel is a perfect model of energy storage device due to its low maintenance cost, long life cycle, high efficiency, free from depth of discharge effects, environmentally friendly, wide operating temperature range and able to survive in harsh condition [61–64]. However, the idling losses are the key issues for viable flywheel construction due to external forces such as magnetic force or friction [65]. The findings of new strong lightweight materials, magnetic bearings and power electronics resulting in greater efficiency and make them even more durable. Although ball bearing's fatigue gets a lot of improvement due to the used of ceramics and very hard steel material, the lubricant life still is the main maintenance issue [60]. The use of composite materials instead of steel allows the significant increase in rotational speed and power density that exceed chemical batteries. Several potential materials for flywheel fabrication are presented in Table 3 [65].

Mechanical bearing is not suitable to be adapted in modern flywheels. A very high rotational speeds lead to high friction and shorter life cycle. In order to solve the issue then the magnetic

Table 5
Comparisons of different types of bearing.

Bearing	Power loss	Advantages	Disadvantages
Ball	5–200 W + due to seals	Simple, low cost, compact	Needs lubrication, seals, hubs and axle
Magnetic	10–100 W	Acts directly on the rotor, can cope with clearance changes	High cost, requires “touchdown bearings” reliability
HTS	10–50 W	Low loss, high forces	Long-term development requirement, housekeeping losses

Table 6
Flywheel shape factor [71].

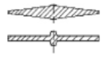
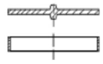
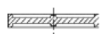
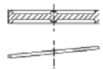
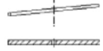
Flywheel geometry	Cross section	Shape factor K
Disc		1
Modified constant stress disc		0.931
Comical disc		0.806
Flat unpierced disc		0.606
Thin firm		0.500
Shaped bar		0.500
Rim with web		0.400
Single bar		0.333
Flat pierced bar		0.305

Fig. 6. Pumped hydro energy storage.

bearing is used. Magnetic bearings can operate without the use of shaft, experience little wear, no moving components, works without lubricant and compromise small internal losses for long-term storage. Different types of magnetic materials are presented in Table 4 [65].

Recently, a new bearing called high temperature superconducting (HTS) were introduced which lead to significant reduction in idling losses, supports quicker switching and lower costs. However, liquid nitrogen is needed for cryogenic cooling purposes [65–69]. Comparisons of different types of bearing are presented in Table 5 [60].

The length and shape of the rotor also influence energy storage capability. Engineers determine the safe zone length the rotor to avoid excitation of the critical part. The specific energy in the rotor's shape characterized by a shape factor is shown in Table 6 [65,70].

Because of their flexibility, the technology is very suitable to be used in storage application that comprise countless charge/discharge cycles and medium-term storage applications such as small scale energy storage [72,73], peak power buffer [73], wind diesel generator [74], photovoltaic system [75], harmonics [76], distribution network [77], UPS and high power UPS system [78,79], aerospace applications [80] and high voltage stator [81]. The use of flywheel as an energy storage device has also been introduced in motorsports, particularly the Formula 1 competition during the 2009 season. The kinetic energy recovery system (or KERS) which uses the kinetic energy generated under braking is recovered and stored in a flywheel for later use. The main drawback of the system is it increases the vehicle's center of gravity height from the ground which causes some unbalance issues on the vehicle due to the reduction of the amount of available ballast weight that is used to predict the behavior of the vehicle while turning [82].

3.3. Pumped hydro energy storage (PHES)

Pumped hydro energy storage has the largest storage capacity as compared to the other energy storage systems. The energy is stored by pumping water uphill using peak-off electricity and then letting the water move downhill and driving the generator to produce electricity for power grid when needed [83]. Installed PHES using fresh water is shown in Fig. 6 [84].

The pumped hydro system firstly was constructed in Italy and Switzerland in 1890 and taken much attention lately in the U.S. at the beginning of 1929 when the Rocky River pumped hydro facility in Connecticut operate successfully [59,85]. At the present, pumped-storage hydroelectricity contributing to 3% of global generation which approximately over 90 GW with the efficiency in the region of 70–85% [85]. PHES plant can be exploited either by using salt or fresh water as storage media. However, until recently, a new idea on underground pumped hydro energy storage (UPHES) has surfaced [15].

The UPHES plant facility uses the same operational methods as a conventional PHES system with the only difference between the two is the location of the reservoir. Proper geological formations and suitable areas are the key factors in the construction of a PHES. The UPHES plant facility as shown in Fig. 7 may be constructed on a flat area depending on the availability of underwater reservoir deep below the surface; and the upper reservoir on the ground level [15]. The global PHES plants are presented in Table 7 [85].

Similar to CAES, large capital cost, highly dependent on the local topography and direct environmental damage caused by the construction of plants is the main drawback of this technology [16]. An ideal site for pumped hydro storage should provide large elevation between the reservoirs, high power potential, large energy storage capacity, insignificant adverse environmental impact and proximity to power transmission lines [86].

Unfortunately, such an ideal site never exists. A new technology is currently being developed to exploit the widely available analogous sites based on PHES design called the gravity power module (GPM). A suspended large piston made from iron and concrete is employed in a deep shaft filled with water to pump the water at ground level. The energy stored by using grid power to force water down and lifting the piston. To produce electricity, the piston drops to force water through the turbine, and drives the generator [86]. The schematic of GPM technology is shown in Fig. 8 [87].

In view of the economic and cost issues, the operation of a GPM plant depends on the excavation of the deep shaft which requires a surprisingly small investment cost. This is due to the lower excavation per storage capacity than the other existing PHES

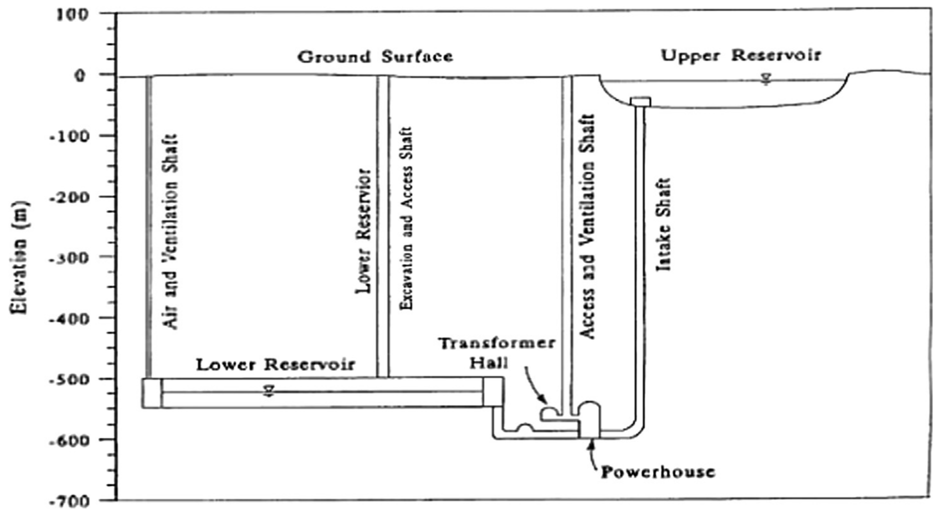


Fig. 7. Underground pumped hydro energy storage.

facilities and it is highly automated. Multi-shaft GPM installations can also be constructed in urban areas due to its small footprint and unobtrusive operation [86].

Another new concept involves the use of wind turbines or solar power to directly drive the pumps. This option could provide a more efficient process and smooth out the variability of energy captured from the wind or sun [87].

4. Electrical energy storage

4.1. Battery energy storage (BES)

The battery uses a chemical reaction to convert the stored chemical energy into electrical energy and produce voltage between terminals. It has become the most common direct current source for many industrial applications and household. There are several promising battery technologies that can be used for grid or hybrid vehicle energy storage systems. The details of various types of batteries will be discussed in the subsequent sections.

4.1.1. Lead-acid (LA)

Lead-acid batteries, the oldest and most developed battery, are a rechargeable battery types and composed of a sponge metallic lead anode, a lead-dioxide cathode and a sulfuric acid solution electrolyte. Having a lot of advantages such as relatively low cost, simplicity of manufacture, quick electrochemical reaction kinetics and good cycle life under measured conditions made them quite attractive and dominate the market [88].

However, the use of heavy metal component is the main drawback of this type of battery which makes them toxic and hazardous to the environment [89]. On the other hand, the utilization of static lead-acid batteries for large-scale application is not favorable and is considered not suitable due to higher cost, limited life span, and practical difficulties in construction [90]. Additives such as calcium, selenium and antimony have also been used by battery manufacturers to improve the performance of lead-acid batteries. Various types of lead-acid battery have been developed namely, Lead Antimony Batteries, SLI Batteries (Starting Lighting and Ignition), Valve Regulated Lead Acid (VRLA) Batteries, Lead Calcium Batteries, AGM Absorbed Glass Mat Battery, Gel Cell, and Deep Cycle Batteries [89].

The problems with static lead-acid batteries lay in the balancing of power consumption and power generation, i.e. load leveling and peak shaving [91,92] which can be solved using lead-acid flow batteries. These relatively new energy storage devices may be coupled with solar and wind energy harvesters that have very unpredictable behaviors due to weather element [92].

In another development, a new hybrid and long life lead acid battery have been introduced to the market with name "Ultra-battery". The ultra-battery can be operated in the continuous Partial State of Charge (PSoC) efficiently without frequent over-charge maintenance cycles. By combining the advantages of an asymmetric capacitor and advanced lead-acid battery technology, Ultra-battery offer an optimum stability with longevity of life and faster charge/discharge with totally full/empty band of charge and potentially used to continually manage energy intermittencies, smooth power, and shift energy [93]. The charge/discharge of the power of the ultra-battery is reported to be approximately 50% higher and three times longer life cycle than the conventional lead-acid battery [94].

4.1.2. Nickel battery

Rechargeable Nickel batteries are classified as secondary batteries and made of active material – nickelous hydroxide as the positive electrode. Among all types of Nickel based battery, Ni–Cd and Ni–MH are the most developed. The other types including that currently available or under development including Nickel–Zinc (Ni–Zn), Nickel–Cadmium (Ni–Cd), Nickel–Metal Hydride (Ni–MH) and Sodium–Nickel Chloride (Na–$NiCl_2$). Even though Ni-–MH and Ni–Cd are widely used in the market, they offer the lowest efficiency compared to others. Compared to Ni–Zn batteries and Na–$NiCl_2$ which offer efficiency of 80% and 90% respectively, they only offer ~70% of efficiency [16].

Ni–Cd batteries use nickel oxy-hydroxide and metallic cadmium as the electrodes. This battery dominates the rechargeable battery segment by the 1990s. Ni–Cd battery come with two designs, sealed and vented. Comparatively inexpensive, fast recharge, long cycle life and capable to withstand deep discharge rates with no damage or loss of capacity are a plus point of this type of battery [95]. Cadmium used within them, although recyclable, is highly toxic and can harm the environment if not treated properly [16].

Another type of nickel-based battery that has been replaced Ni–Cd battery in many applications especially in small rechargeable batteries called Ni–MH. Compared to the same size Ni–Cd cell, Ni–MH batteries offer 30 to 40% more energy capacity and power capabilities which make them capable to meet the high power

Table 7
PHPS around the world

Location	Plant name	Online date	Hydraulic head (m)	Max total rating (MW)	Hours of discharge	Plant cost
Australia	Tumut 3	1973	–	1690	–	–
China	Tianhuangping	2001	590	1800	–	$ 1080 M
	Guangzhu	2000	554	2400	–	–
French	Grand maison	1987	955	1800	–	–
Germany	Markersbach	1981	–	1050	–	–
	Goldisthal	2002	–	1060	–	$ 700 M
Iran	Siah Bisheh	1996	–	1140	–	–
Italy	Plastra edolo	1982	1260	1020	–	–
	Chiotas	1981	1070	1184	–	–
	Presenzano	1992	–	1000	–	–
	Lago delio	1971	–	1040	–	–
Japan	Imaichi	1991	524	1050	7.2	–
	Okuyoshino	1978	505	1240	–	–
	Kazunogowa	2001	714	1600	8.2	$ 3200 M
	Matanogawa	1999	489	1200	–	–
	Ohkawachi	1995	411	1280	6	–
	Okukiyotsu	1982	470	1040	–	–
	Okumino	1995	485	1036	–	–
	Okutataragi	1998	387	1240	–	–
	Shimogo	1991	387	1040	–	–
	Shin takesagawa	1981	229	1280	7	–
	Shin toyne	1973	203	1150	–	–
	Tamahara	1986	518	1200	13	–
Luxemborg	Vianden	1964	287	1096	–	–
Russia	Zagorsk	1994	539	1200	–	–
	Kaishador	1993	–	1600	–	–
	Dneister	1996	–	2268	–	–
South Africa	Drakensbergs	1983	473	1200	–	–
Taiwan	Minhu	1985	310	1008	–	$ 866 M
	Mingtan	1994	380	1620	–	$ 1338 M
UK/Wales	Dinorwig	1984	545	1890	5	$ 310 M
USA/CA	Castaic	1978	350	1566	10	–
USA/CA	Helms	1984	520	1212	–	$ 416 M
USA/MA	Nothrfield Mt	1973	240	1080	10	$ 685 M
USA/MI	Ludington	1973	110	1980	9	$ 327 M
USA/NY	Blenheim–gilboa	1973	340	1200	12	$ 212 M
USA/NY	Lewiston–Niagara	1961	–	2880	20	–
USA/SC	Bad creek	1991	370	1065	24	$ 652 M
USA/TN	Racoon Mt	1979	310	1900	21	$ 288 M
USA/VA	Bath county	1985	380	2700	11	$ 1650 M

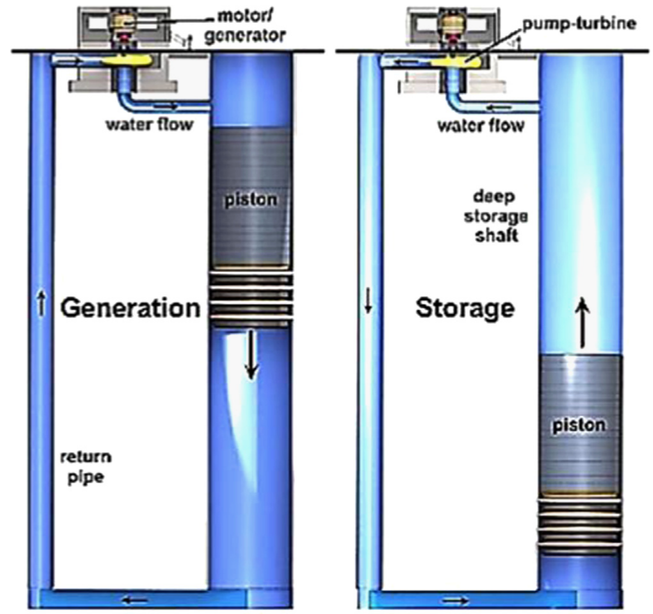


Fig. 8. Gravity power module [87].

requirements in hybrid electric vehicles (HEV) such as the Toyota Prius [95] and are used in over 95% of all HEVs [96]. Due to their design flexibility in the range 30 mAh to 250 Ah range, environmental friendly, low maintenance, high power and energy densities, and safe during the cycles of charging and discharging at high voltages, Ni–MH batteries are favorable in many applications [96]. Compared to Ni–Cd batteries, Ni–MH batteries are more environmentally friendly [16].

4.1.3. Sodium-sUlfur (Na–S)

Sodium sulfur (NAS) battery is an advanced secondary battery has been pioneered in Japan since 1983 by the Tokyo Electric Power Corporation (TEPCO) and NGK [97]. A Na–S battery consists of molten sodium (−) and molten sulfur (+) as active materials parted by a solid beta alumina ceramic electrolyte. It is the most developed type of high temperature battery, though relatively new in power system applications. Due to its outstanding energy density, high efficiency of charge/discharge, zero maintenance, fabricated from inexpensive materials and long life cycle of up to 15 years made it attractive for use in relatively large scale battery energy storage system applications [16].

However, it is reported that there are several conditions that limit the applications to large scale stationary systems. High temperature condition that require to maintain the sulfur in its molten form addressed as small threat to the operators and environment [16]. Moreover, the system must be protected from reacting with atmosphere as pure sodium explodes instantly in contact with air. In addition, the endurance in the harsh chemical environment causes a corrosion in insulators thus the battery became conductive and the self-discharge rate increased [98].

In quest for searching new and safe alternative Sodium sulfur battery, $NaNiCl_2$ battery invented by the Zeolite Battery Research Africa Project (ZEBRA) battery sparked the development of Sodium sulfur battery with long cycle life, inherently safer design, slightly cooler operated temperature and higher voltage compare to conventional Na–S battery [95].

4.1.4. Lithium battery

Lithium batteries are primary batteries composed from lithium metal or lithium compounds as an anode. The advantages such as lightweight, safe, abundant and low cost cathode material make them a promising technology for future mobile applications. Li batteries offer higher charge densities of 100–150 Wh/kg and have limited environmental impact since the lithium oxides and salts can be recycled. However, the high cost of the battery due to special packaging and internal overcharge protection circuit Lithium batteries is their main obstacle to compete with another type of battery [16].

The investigation of advanced lithium energy storage systems has been done in the past decades. The new advanced Li batteries developed by Yi Cui using nanowires silicon are capable to produce 10 times electricity of existing Li-ion batteries. The significant improvement of storage capacity makes Li-ion batteries become more attractive to electric car manufacturers. In the past, the electrical storage capacity of a Li-ion battery is restricted by

Table 8
Characteristic of some flow battery system.

System	Reaction	E^{*}_{cell} (V)	Electrolyte
Redox All vanadium	$\text{Anode}: V^{2+} \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} V^{3+} + e^-$ $\text{Cathode}: VO_2{}^+ + e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} VO^{2+}$	1.4	Anode/cathode H_2SO_4/H_2SO_4
Vanadium-polyhalide	$\text{Anode}: V^{2+} \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} V^{3+} + e^-$ $\text{Cathode}: \frac{1}{2}Br_2 + e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} Br^-$	1.3	VCl_3–HCl/NaBr–HC
Bromine-polysulfide	$\text{Anode}: 2S_2{}^{2-} \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} S_4{}^{2-} + 2e^-$ $\text{Cathode}: Br_2 + 2e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} 2Br^-$	1.5	NaS_2/NaBr
Iron–chromium	$\text{Anode}: Fe^{2+} \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} Fe^{3+} + e^-$ $\text{Cathode}: Cr^{3+} + e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} Cr^{2+}$	1.2	HCl/HCl
H_2–Br_2	$\text{Anode}: H_2 \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} 2H^+ + 2e^-$ $\text{Cathode}: Br_2 + 2e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} 2Br^-$	1.1	PEM*–HBr
Hybrid Zinc–bromine	$\text{Anode}: Zn \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} Zn^{2+} + 2e^-$ $\text{Cathode}: Br_2 + 2e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} 2Br^-$	1.8	$ZnBr_2/ZnBr_2$
Zinc–cerium	$\text{Anode}: Zn \overset{charge}{\Longleftarrow}\overset{discharge}{\Longrightarrow} Zn^{2+} + 2e^-$ $\text{Cathode}: 2Ce^{4+} + 2e^- \overset{charge discharge}{\Longleftarrow\Longrightarrow} 2Ce^{3+}$	2.4	CH_3SO_3H (both)

* Polymer electrolyte membrane.

the amount of lithium can be held in the battery's anode. In conventional Li battery, carbon is used as anode. However, instead of storing in carbon, by store the lithium in a mesh of tiny silicon nanowires with a diameter 1000th the thickness of a sheet of paper, a significant increase in the amount of lithium stored in the battery can be achieved resulting in higher energy density [99].

4.1.5. Metal-air battery

Metal-air battery is the most compact and potentially the cheapest battery available in the market. Instead of an aqueous solution as its electrolyte; the battery uses ionic liquids. The most advanced metal-air systems developed to date are the zinc-air and lithium-air batteries, although other metal electrodes have a higher theoretical energy density. Between the two; Li-air batteries have a higher limit of specific energy. However, Zn-air batteries have an advantage over the Li-air battery systems due to their inexpensive material and are environmentally safer [100]. However, the applications of metal air battery are limited to small-scale uses which the fuel cells are mechanically refueled such as hearing aids or systems in [101]. The low efficiency of around 50% due to the inefficient electrical recharging is the main disadvantages of this battery [16].

4.2. Flow battery energy storage (FBES)

Similar to a conventional battery, flow battery converts chemical energy directly into electrical energy by chemical reactions. However, the electro-active material is stored externally in two tanks of electrolysis and produces the energy by reversible electrochemical reaction between two electrolytes. These systems have quoted efficiencies varying from 70% (cerium zinc) to 85% (vanadium redox). There are four types of flow battery currently being produced or in the late stages of development; zinc bromine, vanadium redox (VRB), polysulphide bromide and cerium zinc. The characteristic of some flow battery system are presented in Table 8 [102].

Modern flow battery systems can be divided into two classes namely redox and hybrid. A redox flow battery is a system in which all the electro-active materials are dissolved in a liquid electrolyte. In the opposite, hybrid flow battery is a system in which one or more electro-active components are stored internally. Most of redox flow battery consists of two separate electrolytes. Both the spent and fresh electrolytes are stored and circulated in a single storage tank or separately to control the electro-active material concentrations [102].

The flow battery offers several advantages compared to conventional battery. The separation between the power and energy requirement, make it possible to design the system to have optimal power acceptance and delivery properties without needing to maximize the energy density. Furthermore, as the electrodes do not undergo physical and chemical changes during operation, more stable and durable performance can be achieved. In addition, the energy capacity of flow battery is addressed by the size of external storage components which make it easy to manage energy density of the battery. Other advantages are it is safer as the active materials separated from the reactive point source, high electricity to electricity conversion efficiency, low maintenance, tolerance to overcharged, and can be deep discharge without affecting the cycle life. However, the complicated system requirement of pumps, sensors, flow and power management and secondary containment vessel make them not suitable for small scale storage application [102].

4.3. Superconducting magnetic energy storage (SMES)

Superconducting Magnetic Energy Storage (SMES) utilizes the magnetic field to store the energy which has been cryogenically cooled to a temperature below its superconducting critical

temperature. The idea of this technology appeared in 1970s to improve the load of French electricity network [103]. However, due to immature technology and cryogenic problems, the plant just operates for one year. In the typical application of SMES, the system consists of three parts namely superconducting coil/magnet, power conditioning system and cryogenically cooled refrigerator [104].

Superconducting coil which considered as the most important part in SMES can be either solenoid or toroid. Solenoid is more simple and easier to control the electric compared to toroid. Although toroid coils quite problematic, it offers low stray field which is considered as an important requirement in SMES applications [105]. Several requirements for a good superconducting magnet are high engineering current densities, low cost, support mechanical deformations and operate in as high as possible temperature. At the present, only NbTi conductors can meet all of the requirements except high operating temperature. An important finding of high critical temperature (HTS) superconducting magnet offers the possibility to operate SMES in higher temperature and reduce cryogenic operating cost which addressed as the main drawback of this technology. Still, higher capital cost compare to NbTi make this technology less desirable. Recently, the second generation of HTS superconducting magnet called "Coated Conductor" is claimed lower cost and operates in higher temperature at 50–60 K instead of 20 K in the first generation [105].

Due to the high cost of superconducting wire and the energy requirements of refrigeration, SMES mostly used for short term energy such as UPS (Uninterruptible Power Supply), pulse power source for dedicated applications and FACTS (Flexible AC Transmission) [105].

4.4. Super capacitor energy storage (SCES)

Super capacitor, ultra capacitors or double-layer capacitors (DLCs) as they are also known is an electrochemical capacitor with relatively high energy density, approximately hundreds of times greater than conventional electrolytic capacitors [106]. The energy stored between a pair of charged plates. Compare to conventional capacitor, super capacitors comprise a significantly enlarged electrode surface area, a liquid electrolyte and a polymer membrane [16]. Apart from that, super capacitor also offers a great advantages over batteries such as the ability to be charged and discharged continuously without degrading [107].

High efficiency and long lifecycle of super capacitor are making the very attractive to be used in many applications. Commonly, super capacitors are used for starting engines, actuators, and in electric/hybrid-electric vehicles for transient load leveling and regenerating the energy of braking. The utilization of super capacitor for regenerative breaking gives a great improvement in vehicle fuel efficiency under stop-and-go urban driving conditions [16].

A newly developed super capacitor by researchers at Nanotek Instruments has been shocking the world as it claims that can store as much energy per unit mass as nickel metal hydride batteries while recharging in seconds. The graphene-based super capacitor have been made using graphene mixed with an acetylene black called Super P that acts as a conductive additive and a binder that holds it all together. This type of battery has energy density 85.6 Wh/kg at room temperature and 136 Wh/kg at 80 °C (176 F), which is comparable to Ni–MH batteries [108].

5. Chemical energy storage

Chemical energy storage is receiving world attention due to its potential to replace petroleum products and reduce greenhouse gas emission significantly. One of the most popular chemical energy storage is hydrogen energy storage. This hydrogen energy storage offers zero emission when it coupled with renewable energy source or low carbon technology. The important components of a hydrogen storage system comprise an electrolyzer unit, the storage component and an energy conversion [16]. Molten Carbonate Fuel Cell (MCFC), Proton Exchange Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Alkaline Fuel Cell (AFC), Solid Oxide Fuel Cell (SOFC), Polymer, and Phosphoric Acid Fuel Cell (PAFC) are several types of fuel cells. Proton Exchange Membrane (PEM) fuel cell, Solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC) are used for reversible electrolyzer operation. For a stationary power generation, Phosphoric Acid Fuel Cells (PAFCs) are the most mature technology high tolerance in impurities within the influx gases compared to the PEM cells which easily poisoned by carbon monoxide (CO) [16].

Moreover, several fuel cell technologies under development namely Direct Methanol Fuel Cells (DMFC), Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFC). SOFCs and MCFCs are anticipated to achieve the efficiency as high as 60% efficiency for the conversion of fuel to electricity and 85% when the waste heat is captured and used and also can be operated at extremely temperature (around 620 °C and 1000 °C respectively) [16].

With low volumetric density 12.7 MJ/m^3 and low boiling point around -273 °C at 1 atm pressure make the liquefaction very energy intensive. The idea to store hydrogen fuel include compressed underground storage in aquifers or salt caverns, chemisorption to metal hydrides and fullerenes, and physisorption to active carbons or carbon nanotubes are under development [16]. Apart of that, carrying hydrogen onboard to travel the same distance as gasoline-powered vehicles is one of the drawbacks of this technology. Even though higher-density liquid fuels such as natural gas, methanol, liquefied petroleum gas, ethanol and gasoline can be used as a fuel to produce hydrogen fuel using fuel cell, the increase cost, maintenance requirement and increase in energy are hindering this idea. In addition, although not as much as conventional gasoline powered engine, fuel cell vehicle will also produce CO_2 emission. Molten Carbonate Fuel Cells (MCFC); Solid Oxide Fuel Cells (SOFC); Direct Methanol Fuel Cells (DMFC) are type of technologies that can be directly converted organic fuel into hydrogen. However, the extremely high operating temperatures make this technology not suitable for transport application. Other fuel cell that offers good potential for transport application are DMFCs and PEM cells [16].

6. Thermal energy storage

One of the most important forms of energy storage is thermal energy storage [109,110]. Applications for TES are very wide, from heating and cooling using waste or solar energy, to high-temperature energy storage for power production and industrial processes [13]. The thermal energy storage system also can be used to increase the flexibility within an energy system. In general, thermal energy storage (TES) can be stored as a change in internal energy of a material as thermochemical, latent heat and sensible heat or a combination of these [111].

6.1. Sensible heat storage system

Sensible heat storage (SHS) method is carried out by adding energy to a material to increase its temperature without changing its phase [112]. In sensible heat storage the quantity of stored heat depends on the temperature change, the heat capacity of the material, and the amount of storing material. In sensible heat storage a solid or a liquid material are used as a storage medium

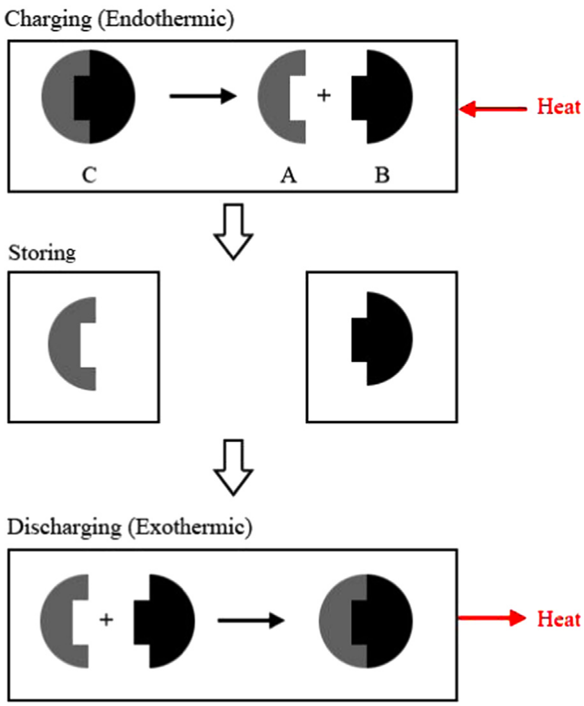


Fig. 9. Charging, discharging and storing processes of a thermochemical heat storage system.

[13]. The storage medium can be water, bricks, sand, rock beds, oil or soil. Together with a container, and input/output device is attached to it to provide thermal energy for any intended application. Most commonly used in dwellings, SHS is used as heat storage to provide hot water for houses and offices. In solar heating systems, water is still used for heat storage in liquid based systems, while a rock bed is used for air based systems [113]. Water as storage material has the advantages of being inexpensive and readily available, of having excellent heat transfer characteristics. For low and high temperature thermal energy storage, solid materials such as metals, rocks, sand, concrete and bricks can also be used [112]. Thousands of materials have been identified that are suitable for the use of thermal energy storage. Fernandez et al. [114] have proposed a proper method of selecting the best material to be used for long and short term sensible energy storage in order to minimize cost. By combining multiple objectives and usage restrictions, they are able to identify appropriate materials through evaluation of cost, availability and environmental aspects such as carbon footprint.

There are a few advantages and disadvantages of both liquid and solid storage medium. For an example, liquid media such as water is widely available and an inexpensive sensible energy storage medium. It is non-toxic, non-combustible, has a relatively high specific heat and high density characteristics, and easy to handle. However, at low or high temperature applications; water might freeze or boil and is thus limited by the melting and freezing point of water. Furthermore, water is highly corrosive and difficult to stratify. To avoid freezing and corrosion problems when using water; chemical additives may be added. Other liquid media such as molten salts, liquid metals and organic oils may be used for applications where water is not suitable [115].

6.2. *Latent heat energy storage*

Latent heat storage (LHS) is based on the heat release or heat absorption during phase change of a storage material from solid to liquid or liquid to gas or vice versa [111]. The phase change process of the material is adapted to store the latent heat thermal energy. There is a visible advantage of PCMs (paraffin wax, salt hydrates, and fused salts) over sensible heat storage materials [13,116]. LHS, compared to SHS, offers higher density of energy storage with near zero temperature changes. However, difficulties usually arise in real due to the low density change, thermal conductivity, sub cooling of the phase change materials, stability of properties under extended cycling and sometimes phase segregation [113].

Phase change materials are specifically used in latent heat energy storage systems, and thus PCM can also be called latent heat storage material. The thermal energy transfer of PCM occurs during the charging or discharging (melting or solidification) process at which the state or phase of the material changes from liquid to solid or from liquid to solid. At the start of the heating of the material, the PCM temperature rises as it absorbs the thermal energy. When the material reaches a specific temperature range; it will start to melt as the material begins to experience a phase transition from solid to liquid state. However, unlike sensible heat storage materials; during the phase transition process the PCM releases or absorbs heat at a constant or nearly constant temperature. Many authors have experimented with different types of PCMs, subdividing them into organic, inorganic and eutectic types. However, the majority of the phase change material does not possess the recommended properties for an ideal thermal energy medium and thus thermal enhancers are used to improve any disadvantages that the medium may have. Extensive discussions for each class of phase change material properties can be referred from [111,117].

6.3. *Thermochemical energy storage*

In thermochemical energy storage system, the energy is stored after a breaking or dissociation reaction of chemical bonds at the molecular level which releases energy and then recovered in a reversible chemical reaction. Similar to the other type of thermal energy storage systems, thermochemical heat storage system may also undergo charging, storing and discharging processes. Fig. 9 illustrates the reversible processes of a thermochemical heat storage system [118].

Additionally, thermochemical heat storage may undergo various processes which include reversible chemical and photochemical reactions, water release from zeolites and hydrates and fuel production. The advantages of this method are the system is more compact due to the higher energy densities compared to SHS and LHS [13]. Furthermore, the system suffers little or no heat loss during the storing period where the two components A and B are stored separately at ambient temperature. Hence, this type of thermal energy storage is more suitable for long-term energy storage i.e. seasonal storage.

In order to select the most suitable candidate for thermochemical heat storage material, several key factors may be used as a rough guideline. These key factors are (i) cost, (ii) ability to sustain large number of charging, storing and discharging cycles, (iii) availability of the material, (iv) non-toxic and non-flammable,

Table 9
Promising thermochemical materials.

Material	Formula	A: solid reactant, B: working fluid	Energy storage density (GJ/m^3)	Charging temperature (°C)
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	A: $MgSO_4$ B: $7H_2O$	2.8	122
Iron carbonate	$FeCO_3$	A: FeO B: CO_2	2.6	180
Iron hydroxide	$Fe(OH)_2$	A: FeO B: H_2O	2.2	150

Table 10
Technical comparisons of energy storage technology.

Technology	System energy density (Wh/kg)	Efficiency of recovery (%)	Development	Capital cost (€/kW)	Advantages	Disadvantages	Suitability for		
							Energy management	Power quality	Transport
Super capacitors	0.1–5	85–98	Developing	200–1000	Long life cycle, high efficiency	Low energy density, toxic and corrosive compound	√ √	√ √ √	√ √ √
Nickel batteries	20–120	60–91	Available	200–750	High power and energy density, good efficiency	NiCd highly toxic, NiZn, NiMH and NA-$NiCL_2$ require recycle	√ √	√ √ √	√ √ √
Lithium batteries	80–150	90–100	Available	150–250	High power and energy density, high efficiency	High cost Lithium oxide & salt require recycling, Polymer solvents and carbon must be made inert	√	√ √ √	√ √ √
Lead acid battery	24–45	60–95	Available	50–150	Low capital cost	Lead require recycling	√ √	√ √ √	√ √ √
Zinc Bromine flow battery	37	75	Early phase of commercialization	900 €/kWh	High capacity	Low energy density	√ √ √	√ √	x
Vanadium flow batteries	–	85	Early phase of commercialization	1280	High capacity	Low energy density	√ √ √	√ √	x
Metal air battery	110–420	~50	Developing	–	High energy density, low cost environmentally benign	Poor electrical recharge ability, short recharge lifetime	√ √ √	√	√
Sodium sulfur battery	150–240	> 86	Available	170	High energy density, high efficiency	High production cost, Na requires recycling	√ √ √	√ √	√
PHES	–	75–85	Available	140–680 m for 1000 MW	High capacity, relatively low cost per unit capacity	Disturbs local wildlife and water level	√ √ √	√ √	x
CAES (Alabama plant)	–	80	Available	400	High capacity, relatively low cost per unit capacity	Problematic in obtaining sites for use	√ √ √	√ √	×
Flywheel	30–100	90	Available	3000–10,000	High power	Low energy density	√ √	√ √ √	√
SMES	–	97–98	Developed up to 10 MW, potential to increase to 2000 MW	350	High power	Health impact for large scale sites	√	√ √ √	×
H_2 fuel cell	–	25–58	Research/ developing/ marketed	6000–30,000	Can stored long term, Range of cell types for different applications	Expensive catalyst or processing often required	√ √ √	√ √ √	√ √ √
H_2 for vehicle	–	–	Developing		–	–	√	√	√ √ √

(v) corrosiveness, (vi) reaction rate and temperature range, (vi) energy storage density and (vii) good heat transfer characteristics and flow properties. A list of selected promising thermochemical materials is tabulated in Table 9 [119].

7. Technical comparison of different types of energy storage

The comparisons of the storage technologies discussed above are presented in Table 10. It shows the technology types, the system energy densities, their technical characteristics, relative development status, illustrative economic costs and suitability for different applications [16].

8. Barriers and issues in deploying energy storage system

There are three key barriers to the expanding energy storage technology as addressed by Elkind, namely [120]:

(1). Regulations and utility processes that disfavor energy storage.
(2). Costs.
(3). Lack of awareness of energy storage benefits

Electricity tariffs regulated by the government usually do not provide explicit regulations on calculating the value of the energy savings offered by energy storage. No clear mechanism to recover the value of electricity from energy storage make the current rate structuring process not ready for this technology. The fact that storage system returns the grid less power than the stored will increase their cost over from the grid rate [121]. The owner/investors usually need to seek approval from the authorities to make adjustments in electricity tariffs. However, benefits usually are not in accordance with the capital cost being the main cause of energy storage technologies are less desirable by the investor. In addition, the lack of methodology to measure savings and the lack of provision of incentives prevent them from considering the energy storage as an alternative rather than build a new transmission lines and power plants which may be more expensive. The solution should be taken by developing new regulations to fully capture the value of energy storage and encourage the developers to invest in storage facilities [120].

In addition, while the cost of some energy storage declining due to their mass production; it is still relatively expensive due their newness and high cost of raw material and the lack of large scale production. The relatively high cost of some technologies compare to conventional technologies with similar power capabilities make it more difficult to attract financing although it offer free carbon. The option of less expensive energy storage such as pumped hydro are hindered by permitting or siting challenges resulting in extra cost. This problem can be solved by developing tax incentives, government support for funding, and streamlined regulatory approvals which make the technology more attractive to investors [120].

Although energy storage has existed since 1970s and set to be green technology in the future, policy maker still unaware of what energy storage are and what benefits get from storage technology. Moreover, no experience in deploying energy storage in large scale makes the policymaker lack a conclusive data about the cost and energy saving capability of the technology. By providing the data, perform studies and promote the findings to the decision maker, will make them realize how important energy storage in the future [120].

9. Conclusions

Energy storage offered a lot of potential due to the capability to improve the performance of the system. By storing the excess energy and use it for peak of time makes the technology more worthy than building a new power plant. Free carbon emission and the potentiality to be integrated with renewable energy would improve the penetration of the technology in the market. However, a further study and more research are necessary as there is no one energy storage technology that has all of the ideal characteristics required for optimal grid integration. By knowing the pros and the cons of each system, the technology most likely will become the best solution for replacing the need of fossil fuel on the electricity network and transportation sector without disregard the other sector.

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